

Environmental Requirements and Verification for NASA' s Planned Europa Clipper Mission

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ABSTRACT

NASA' s Jet Propulsion Laboratory (JPL) and its partner are planning a mission to explore an icy moon of Jupiter, Europa. The objective of the planned Europa Clipper mission is to gain insight into the key ingredients for this potentially habitable world. This mission will conduct investigations using a suite of instruments that includes a set of five remote sensing instruments, four in-situ fields and particles instruments, and a two-channel ice-penetrating radar. Among its science objectives are to produce high-resolution images of Europa' s surface, determine its composition, look for signs of recent or ongoing activity, measure the thickness of the ice shell, search for subsurface lakes, and determine the depth and salinity of Europa' s ocean.

Europa Clipper is expected to encounter a very challenging environment, particularly in radiation. This paper provides a comprehensive description of the challenging environments and the environmental requirements that are levied onto the Europa Clipper system design. The mitigations activities being conducted or planned to ensure compliance with the severe environments will be described. Also discussed will be how the environmental requirements are verified and at which level of integration to ensure mission success.

INTRODUCTION AND MISSION OVERVIEW

The exploration of Jupiter' s moon, Europa, is ranked as one of highest priority in the Planetary Decadal Survey. The Europa Clipper Project is the result of many years of mission concept studies. The primary exploration objective of the planned Europa Clipper mission is to

investigate Europa's habitability and gain insight into the key ingredients: water, chemistry, and energy; which make a planet potentially habitable. The three science objectives for the mission are, to:

1. Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange;
2. Understand the habitability of Europa's ocean through composition and chemistry;
3. Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

Europa Clipper is expected to launch as early as June 2022. Currently, there are two Jupiter system delivery options being considered: 1) the baseline mission is an Earth-Jupiter direct trajectory launching on the powerful NASA Space Launch System (SLS) launch vehicle, with a 2.7-year cruise time; and 2) an Earth-Venus-Earth-Earth-Gravity-Assist (EVEEGA) trajectory launching on an Evolved Expendable Launch Vehicle (EELV) launch vehicle to provide sufficient interplanetary velocity for a Jupiter transit, with a 7.5-year cruise time. The SLS direct and EELV EVEEGA trajectories are shown in Figure 1.

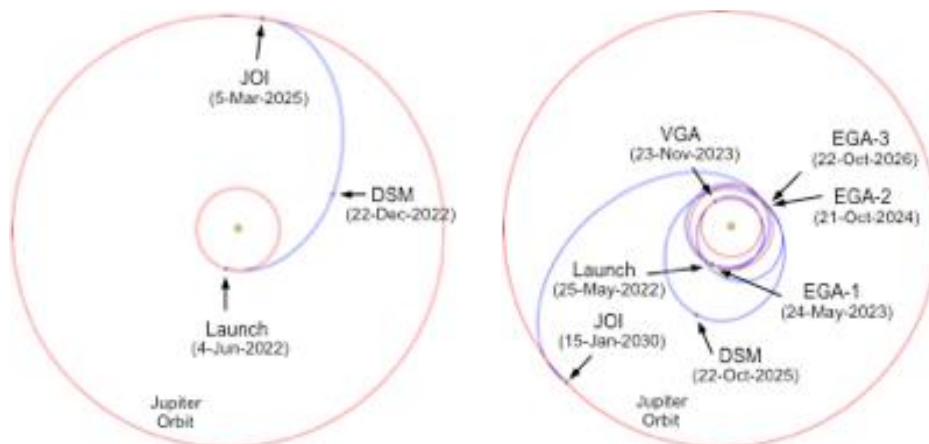


Figure 1. SLS Direct (left) and EELV EVEEGA (right) Trajectories

The current Europa Clipper approach employs multiple (40-45) flybys of Europa in a nominal ~ 14 day Jovian highly-elliptical orbit to limit the exposure of the flight system to the extreme radiation environment. This approach limits the time spent in the high radiation environment at close flybys of Europa, while allowing 2 weeks in between flybys for data downlink in environmental conditions that pose less threat

to the spacecraft operations, thereby extending the lifetime of the mission and maximizing the total science return. The closest-approach altitudes from the surface of Europa vary from several thousand kilometers to as low as 25 kilometers. The flybys will be executed over approximately 3.5 years of prime mission duration. A representative tour design is shown in Figure 2.

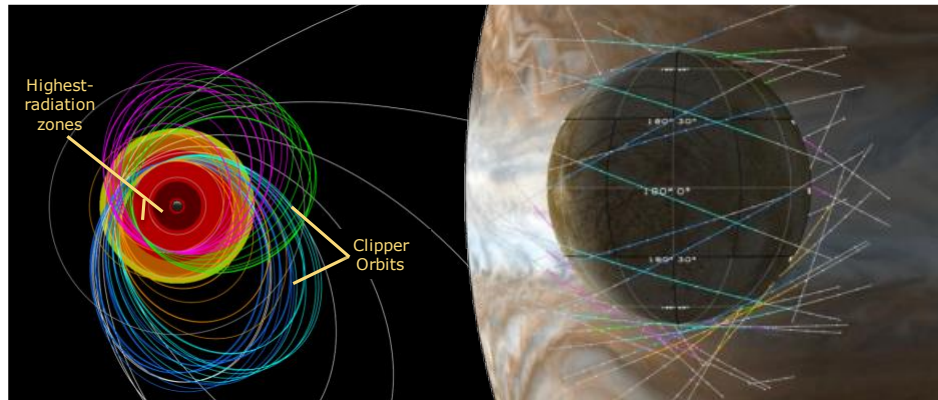


Figure 2. Example of the Multiple Flyby Tour Design.

FLIGHT SYSTEM DESCRIPTION

The flight system is comprised of a spacecraft (S/C) and 9 selected instruments, as illustrated in Figure 3 and Figure 4 for the launch and flyby configurations.

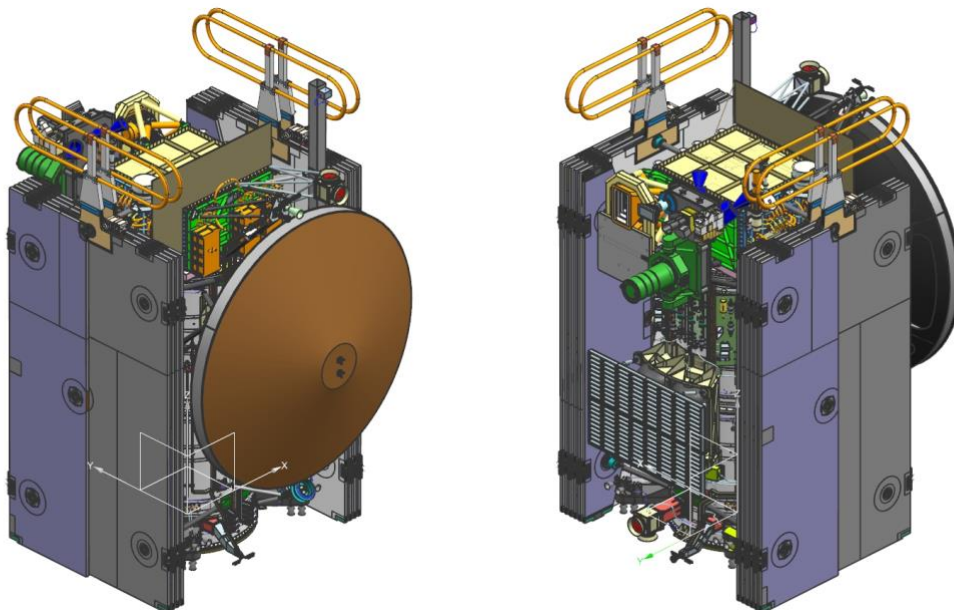


Figure 3. Europa Clipper Flight System in the Launch Configuration,

2 views.

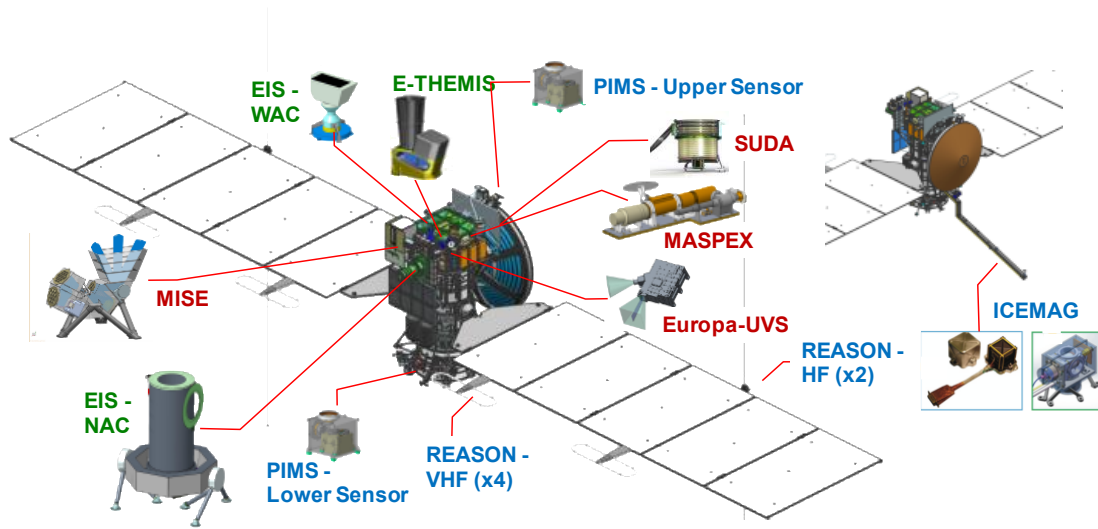


Figure 4. Europa Clipper Flight System in the Flyby Configuration Indicating the Instruments Location.

The S/C consists of three main modules: the avionics module, the RF module, and the propulsion module. The avionics module (on top of the S/C) consists of a radiation vault that houses the guidance/navigation/control components, power electronics, batteries, radiation monitor, avionics, and majority of the instrument electronics. The radiation vault is designed to limit the radiation dose for the electronics inside.

The RF module consists of the S/C structure and thermal control elements that comprise much of the telecommunications subsystem. This subsystem performs all the functions needed to receive commands from Earth, transmit telemetry back to Earth, support radiometric navigation, and provides radiometric support to the gravity science investigation. The 3m diameter high gain antenna (HGA, for X-band uplink and both X- and Ka-band downlink), the medium and low gain antennas (MGA, LGAs at X-band), and the fan beam antennas (used to provide signal coverage for gravity science during the Europa flybys at X-band) are all mounted to the propulsion module structure.

The propulsion module consists of the S/C structure and thermal control elements that support the bi-propellant propulsion subsystem. This subsystem performs the functions necessary to provide thruster based attitude control, reaction wheel momentum desaturation, and delta-V

maneuvers. It includes the propulsion module electronics (located inside a mini-vault for radiation protection), that distributes power and commands (using thruster and valve control) and collects telemetry from the propulsion module. The propulsion module also includes the large, ~90m², solar arrays for spacecraft power generation.

The science objectives will be achieved utilizing a comprehensive set of both remote sensing and in-situ instruments:

- Europa Imaging System (EIS), composed of both a narrow angle camera (NAC) and a wide angle camera (WAC), to constrain the formation of surface features, characterize the ice shell, and characterize the surface at the small scale;
- Mapping Imaging Spectrometer for Europa (MISE), to understand the inventory and distribution of surface compounds, investigate the geological history of the surface, and search for areas that are currently geologically active;
- Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON), to characterize the distribution of any subsurface water, search for an ice-ocean interface and characterize the ice shell's global thermophysical structure, investigate the processes governing material exchange among the ocean, ice shell, surface, and atmosphere, constrain the amplitude and phase of the tides, and characterize scientifically compelling sites, and hazards, at a small scale;
- Europa Ultraviolet Spectrograph (UVS), to characterize the global structure and composition of the atmosphere, search for and characterize any plumes, explore the surface composition and microphysics and relation to endogenic and exogenic processes, and investigate energy and mass flow into Europa's atmosphere, neutral cloud, and plasma torus;
- Europa Thermal Emission Imaging System (E-THEMIS), to detect and characterize thermal anomalies that may indicate recent activity, search for active plumes, and determine the regolith particle size, block abundance and subsurface layering for surface process studies;
- SURface Dust Mass Analyzer (SUDA), to map the surface composition, characterize the alteration of the surface via exogenous dust, and determine the composition of the particulate matter in active plumes, if present;

- Mass Spectrometer for Planetary EXploration / Europa (MASPEX), to determine the distribution of major volatiles and key organic compounds in the exosphere/plumes and their association with geological features and determine the relative abundances of key compounds to constrain the chemical conditions of Europa's ocean;
- Interior Characterization of Europa using MAGnetometry (ICEMAG), to determine the location, thickness, and salinity of Europa's ocean by magnetic field induction at multiple frequencies, identify sources of Europa's atmosphere and atmospheric loss processes by characterizing any active vents, plumes, and ionized plasma trails, and understand coupling of Europa to Jupiter's ionosphere and coupling of any plumes to flowing plasma;
- Plasma Instrument for Magnetic Sounding (PIMS), to determine Europa's magnetic induction response as corrected for plasma contributions, to estimate ocean salinity and thickness, to understand mechanisms of weathering and release of material from the surface into the atmosphere, and to understand how Europa influences its local space environment.

In addition, the spacecraft's telecommunications subsystem will be used to characterize Europa's time-varying gravitational tides in order to confirm the existence of Europa's subsurface ocean.

MISSION ENVIRONMENT CHALLENGES

Europa Clipper is expected to encounter a very challenging environment. The region near Jupiter, including Europa, has one of the most severe radiation environments in the solar system. The mission trajectory ranges from ~0.65 AU, during Venus gravity-assist, to ~5.6 AU near Europa, providing a wide-range of solar thermal environments that can cause wide temperature swings. Since several launch vehicles are being considered for delivering the flight system, the system design needs to address compatibility issues with the worst-case envelop of multiple launch vehicle environments. Furthermore, the flight system must be compatible with the challenging magnetic cleanliness and EMI requirements, since there will be sensitive magnetometers and a HF/VHF radar on board.

In this section, a comprehensive description of the environments encountered by the Europa Clipper mission will be provided, with emphasis on the critical environments. Extensive mitigation

activities, which are on-going to reduce the adverse effects on the mission, will be highlighted. The derived environmental requirements levied onto the flight system design will be summarized. The method of verification for each environment: by modeling, testing, or analysis; or at which level of integration: at the component, assembly/subsystem, instrument, or spacecraft/flight system level, will be summarized.

RADIATION ENVIRONMENT

Ionizing radiation is the primary driving environment for the Europa Clipper mission. Since Jupiter has a high magnetic moment, much higher than Earth's, the trapped radiation environment is resulting in the severe radiation environment. Europa lies well within the Jovian radiation and plasma environment, therefore the radiation flux level at Europa is high, as illustrate in Figure 5.

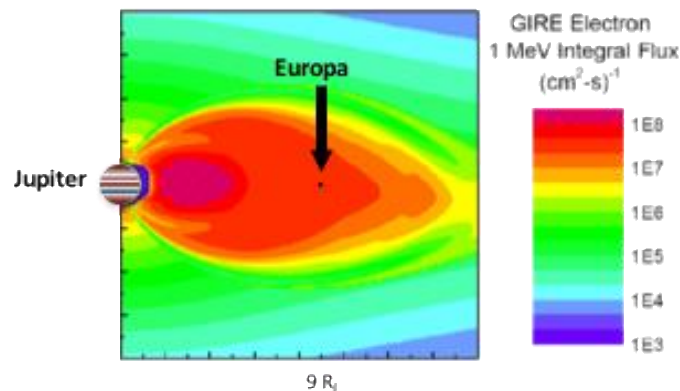


Figure 5. An illustration of Europa in the High Jovian Radiation Environment.

The ionizing radiation exposure of Europa Clipper flight hardware will come primarily from high-energy electrons and protons in the Jovian radiation belt. The trapped particle mission integral fluence energy spectra are shown in Figure 6.

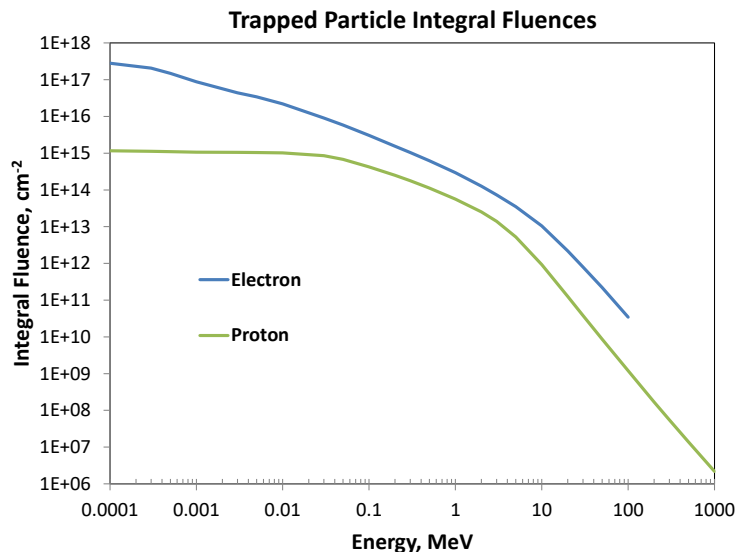


Figure 6. Trapped Particle Integral Fluences for the Notional Mission Profile.

The high-energy electrons and protons can cause Total Ionizing Dose (TID), Displace Damage Dose (DDD), Single Event Effect (SEE), and Internal Electrostatic Discharge (iESD) effects. (iESD is an important effect for the Europa Clipper mission and it will be described in more detail later in this section.) These effects can cause electronic failure, material degradation, and/or background noise in science sensors and detectors.

Figure 7 shows the TID-Depth Curve derived from the mission fluence energy spectra for inside an aluminum spherical shell at various shielding thicknesses. Note that the TID level behind 100 mils of Al is 3 Mrads(Si), which is used as a design criteria for the Europa Clipper mission requirement.

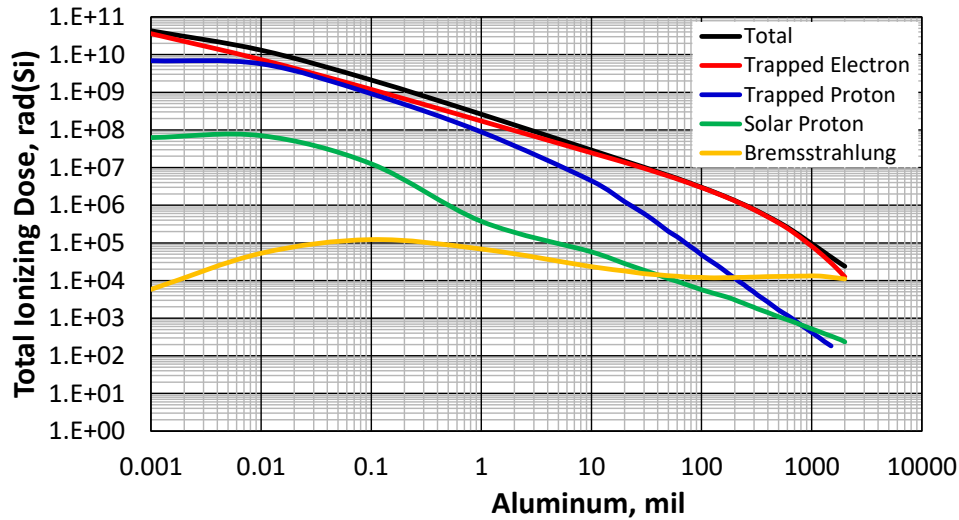


Figure 7. TID-Depth Curve for the Notional Mission Profile.

Radiation Effects Mitigation

The Europa Clipper project has employed a number of strategies to mitigate the effects of radiation/plasma environment, as outlined below:

1. Since surviving the total radiation dose is a driving technical challenge, the tour is designed innovatively, by minimizing the mission exposure time in the high radiation environment, to limit the maximum ionizing radiation dose to 3 Mrad (Si) behind 100 mil of Al sphere at end-of-mission.
2. A radiation design factor (RDF) of 2 is used for TID and DDD when determining the acceptability of a device for project use. This RDF, defined as the ratio of the part's radiation tolerance over the part's radiation levels at the location, is to take into account any uncertainty in the variability of the environments and that the time-averaged Jovian environment model is used to calculate the mission TID and DDD fluences.
3. All major electronics are housed inside a radiation-protection "vault." The vault is designed with appropriate thickness of shielding material to reduce the TID level inside the vault down to 150 Krad(Si). Other device/subsystem electronics not in the vault are required to be separately shielded in localized enclosures with the same RDF of 2.
4. Radiation-hardened electronic parts are selected for 300 Krad(Si) radiation tolerance inside the vault. This will meet the TID

requirement of 150 Krad(Si) with an RDF of 2. For those electronics that do not meet this requirement, local shielding will be necessary, because the charging during 40-hour time period cannot be bled off within 2 weeks.

Electrostatic Discharge Effects Mitigation

Electrostatic discharge (ESD) is basically a charge buildup on surfaces. Whereas internal ESD (iESD) is charging imbedded inside the bulk of dielectric materials or floating conductors. It is sometimes referred to as deep dielectric charging or bulk dielectric charging.

The energetic electrons encountered by the Europa Clipper flight system can penetrate the structural elements or electronics chasses and deposit their charges inside the dielectrics or floating metals. The charges will accumulate over time that will result in arcing or electrostatic discharges, if the electric field becomes larger than dielectric strength. This can lead to damage of sensitive electronic components in circuit boards or electronics devices, and can lead to mission failure.

For the Europa Clipper mission, nearly all the high-energy electrons accumulation occurs during a ~40-hour time period of closest approach to Europa for each 2-week long tour. The iESD design environment is specified based on the worst-case 40-hour electron fluence, with a 5-times safety factor, corresponding to a 95 percentile survival rate, to account for the variability of the environments. This environment is being used for iESD charging assessments of floating conductors and dielectrics materials whose resistivity is $<10^{19} \Omega \text{ cm}$. For dielectrics with a resistivity $\geq 10^{19} \Omega \text{ cm}$, a more rigorous assessment will be made.

A set of guidelines has been issued to assist subsystem designers in minimizing the occurrence of iESD. Increasing shielding to reduce the high-energy electron flux would be the most effective. Detailed, specific guidelines have been provided for dielectric materials, floating metals/conductors, and cables usage and dimension.

In order to ensure the requirements and guidelines are correct with high confidence, a set of representative cables and floating wire of various lengths have been exposed to the equivalent electron beam doses

with the iESD transient effects characterized. Also, specially designed circuit boards with dielectrics and floating metals of various sizes have similarly been tested with electron beams to confirm the guidelines are valid. In addition, a charging software code has been used for 3-D simulation of the charging effects to confirm the validity of the test results. Eventually the verification for compliance with the iESD requirements is through careful review of the size, location, and properties of the dielectric materials and floating metals used throughout the subsystems.

Electronic Parts Selection and Evaluation

The radiation and reliability challenges of the Europa Clipper mission are driving factors in the selection of suitable microelectronics technologies with acceptable radiation characteristics and long-term reliability. Extensive characterization and radiation testing of all required electronics part types that would potentially survive the desired 300 Krad(Si) radiation dose is currently under way. Electronics parts that meet the radiation tolerance requirements of the project will be placed in an approved parts list from which subsystems and instruments can select for their electronics design. Reliability analyses, such as parts stress, worst case, etc., will also be performed to verify that the electrical circuits will function within specification in this high-radiation environment.

Materials Selection and Evaluation

Many materials are susceptible to radiation effects. Materials that are unshielded or partially-shielded can experience hundreds of Mrads(Si) or even Grads(Si) TID levels. Radiation testing of an extensive set of materials, e.g. wire harnesses, multilayer insulations, heaters, platinum resistance thermometers, solar array adhesives, wire spot bonding products, solar array coverglass bonding silicone, solar array laminate and honeycomb materials, are currently under way. Some of the radiation testing is performed in conjunction with the thermal environments, which involve subjecting them to additional thermal cycling testing at very hot (up to 195°C) or extreme cold temperatures (down to -240°C). The acceptable materials will be placed in a preferred materials selection list from which subsystems and instruments can select for their design applications. Materials

that are not on the list will need additional verification by testing or analysis to meet the mission radiation environments as well as surviving thermal cycling.

Guidelines have been issued for specific application of certain materials. All subsystems and instruments will need to provide a material utilization list to be reviewed and approved by the project material engineer to ensure all materials satisfy their performance under the mission environments.

EMI/EMC/MAGNETICS ENVIRONMENT

The Europa Clipper Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC), and magnetics design and test requirements are based on MIL-STD-461/462, but tailored to have more stringent EMI quietness and magnetics cleanliness requirements based on instruments' needs. A comprehensive set of preliminary EMI/EMC/magnetics requirements has been generated as part of the EMC design and verification program, which is intended to produce a flight system that would be electromagnetically compatible with itself and its external environment during all mission phases. This includes performance-compliant flight system operation in orbit and in the launch environment with the launch vehicle and launch site under all mission operation conditions. These requirements are levied on the flight system, as well as on its instruments, subsystems, and assemblies throughout their mission duration.

The Europa Clipper radiated emission (RE102) requirements are primarily driven by the REASON instrument which has operating frequencies centered at 9 MHz and 60 MHz. Any electronic equipment with clocks or oscillators has the potential of having harmonics that fall within the 9 MHz or the 60 MHz receiver bands, and would interfere with the REASON instrument receiver bands. The command and data handling equipment is also a noise source at these frequencies during data transmission. This requires severely limiting the RE102 radiated emission at those frequencies.

The Europa Clipper radiated susceptibility (RS103) requirements are also influenced by the REASON transmitter characteristics. Flight system operational subsystems and instruments must function properly within specified performance while exposed to the radiated E-fields

transmitted by the REASON HF and VHF antennas. Figure 8 shows sample simulation results of the 9 MHz and 60 MHz REASON transmitter E-field levels, which are used for determining the radiated susceptibility, RS103, levels for each location. The plot also indicates the regions with the worst field levels where mitigations may be necessary to reduce the fields.

The Europa Clipper magnetic emission requirements are driven by the sensitive ICEMAG and PIMS instruments: 5 nT at the ICEMAG outboard magnetometer sensor and 250 nT at the PIMS sensor. To meet these requirements, the flight system total magnetic field contribution must be limited. In order to develop the magnetics emission requirements for each subsystem and instrument, a model has been set up to simulate the magnetics levels throughout the flight system using over 150 identified magnetic sources of concern. These sources are primarily coming from the instruments, guidance and control subsystem, and telecommunication subsystem. They were inputted into the model to predict the magnetic field at different locations of the flight system. From this model, each component has been allocated a magnetic moment and magnetic field requirement to enable the magnetics requirements at the ICEMAG and PIMS locations to be met.

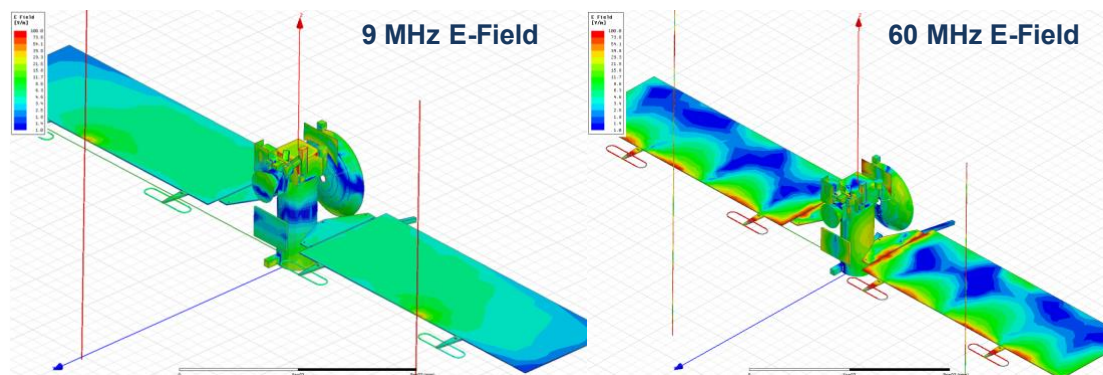


Figure 8. REASON Instrument E-Field Simulations at 9 MHz and 60 MHz.

A set of implementation guidelines has also been issued to assist in designing EMI/EMC and magnetically compliant hardware. Central to the compliance is performing the specified EMI/EMC/magnetics testing at the lowest level of assembly early to mitigate the risk before integrating into the subsystem or instrument. A detailed suite of EMI/EMC/magnetics verifications (test, analysis, inspection) will be

performed when all the subsystems and instruments have been integrated into the flight system to ensure full self-compatibility.

DYNAMICS ENVIRONMENT

The main driver for the Europa Clipper dynamics design environment is the need to maintain compatibility with multiple launch vehicles. This environment includes random vibration, acoustics, and shock. Since some of the launch vehicles being considered have never been flown before, there is some uncertainty in their environments. Therefore, the dynamics requirements are derived conservatively by enveloping the worst-case levels, plus margins, for all potential launch vehicles.

Random Vibration Environment

The random vibration environment is induced by a combination of: a) vibration transmitted mechanically through the base of the spacecraft and b) vibration of the spacecraft structure excited acoustically. It consists of broadband excitation in the mid-frequency range from 20 to 2000 Hz. Preliminary vibration environment, specified in terms of interface Acceleration Spectral Density (ASD) curve, has been derived using the Finite Element Model for the flight system. Similar preliminary random vibration ASD curves have also been derived for different flight system zones, with 13 major zones and some sub-zones. Each assembly, subsystem, or instrument is assigned to one of the zones. The root-mean-square g levels in the zones range from 5.5g_{rms} for the heavy propellant tanks to as high as 23.3g_{rms} for lighter antennas mounted on the edge of the solar array.

Random vibration is JPL's most-widely adopted workmanship dynamics testing for spaceflight hardware at the assembly, subsystem, or instrument level. All flight articles are required to undergo a random vibration test, usually performed on a shaker, according to the levels and durations specified for the component in the appropriate zone and they must be within the specified tolerances. A low-level random survey is usually performed to identify the resonant frequency first. The test article will be required to be in its flight configuration with all flight interface attachments. The random inputs will be applied in each of three orthogonal axes in the test. The test articles may be force-limited, with accelerometer monitors placed in sensitive locations, during vibration testing to prevent over-testing. Any

equipment that is powered-on during launch, such as the flight computer, needs to be powered-on during the random vibration testing. This is to demonstrate its capability to survive and meet all performance requirements during and after exposure to the vibration environment.

After the assemblies, subsystems, and instruments have been integrated as a flight system, it will undergo another random vibration test. This test validates the capability of the fully-assembled flight system to withstand the flight vibration environment and screens for workmanship before launch. Testing at this higher level of integration, however, is at a lower excitation level than testing at the component level.

Shock Environment

Shock environment is the result of high-frequency mechanical transients induced by separation, release, and deployment mechanisms. The Europa Clipper shock environment is due to the flight system/launch vehicle separation, ICEMAG boom launch restraints release, REASON antennas deployment, several instruments' cover deployment, gimbal launch locks release, vacuum covers release, etc. These shock devices include separation nuts, pin-pullers, Frangibolts, and other Non-Explosive Actuators (NEA) devices.

Shock environment is specified as Shock Response Spectrum (SRS) and at the Maximum Expected Flight Level (MEFL) g levels. The maximum predicted shock levels at the flight system/launch vehicle interface is estimated to be 5000g peak SRS. Maximum predicted MEFL shock levels have been predicted for all assemblies/subsystems and instruments throughout the flight system, based on the intensity level of all the shock sources, the distance and the type/number of structural joints between the component and the shock sources. They range from 850g to 3200g peak SRS for qualification/protoflight testing which included a safety margin of 1.4.

Pyroshock testing is required for all assemblies and instruments containing shock-sensitive components, such as electronic equipment, switches, and brittle materials, and also exposed to pyrotechnic shock loading of greater than 750g, whether the loading is self-generated or induced by external sources. A shock qualification test can be

performed using a flight-like engineering unit with 2 shocks per axis or performing a protoflight test using the flight unit with only 1 shock per axis, applied at the mounting points in each of three orthogonal axes. Several test apparatuses can be used to simulate shock environment: a shaker, resonant beam, MIPS (Mechanical Impulse Pyro-Shock) table, drop test, or device firing. At JPL, pyroshock simulation testing is usually performed using a MIPS table for assemblies. Sometimes it may be possible to achieve the specified levels in two or more axes simultaneously. If the test article is too large or heavy for the MIPS table, device firing testing is performed with 2 firings.

After the assemblies, subsystems, and instruments have been integrated as a flight system, it will undergo a device firing test. Two firings of the dominant shock sources, such as the flight system/launch vehicle separation pyrofiring, and one firing of all other shock sources will be performed.

Acoustics Environment

Acoustic noise environment is due to high-frequency excitation by the acoustic field inside the launch vehicle payload fairing. The acoustic noise requirement is specified as Sound Pressure Level (SPL) in dB and in terms of 1/3-octave band averages and overall SPL level.

The Europa Clipper acoustic noise spectra have been specified, which is the envelope of the predicted acoustic environments for the candidate SLS Block 1/1B and EELV launch vehicles. The maximum acoustic environment for the Europa Clipper flight system occurs during lift-off and transonic flight. The current predicted environment overall SPL protoflight level is at 146.9 dB, which is higher than most typical missions. The qualification test duration is 2 minutes and the protoflight test duration is 1 minute. Acoustics testing is required for hardware with high surface-to-mass ratios, i.e. large, low-density panel structures. An acoustics test is planned for the integrated flight system as a high-frequency workmanship testing. Currently only two susceptible assemblies have been identified that require acoustic testing: the solar arrays and the high gain antenna.

The acoustic tests will be performed in JPL's reverberant chamber. The test article will be suspended or otherwise positioned in the

acoustic chamber on a low frequency suspension system. The test article will be situated so that a minimum of two feet (0.61 m) away from any chamber wall. A reverberant field of the required SPL is created inside and measured at four or more microphones spatially distributed around the test article. An average measured SPL is fed back into control loop to maintain the average SPL, in each 1/3-octave band and the overall SPL level, to within the specified tolerances.

Induced Microphonics Environment and Jitter Effects

Microphonics is the conversion of mechanical vibrations into undesired electrical noise signal by certain components in electronic devices, and jitter is the smearing of images in optical systems or pointing disturbances (for cameras or stellar reference units) caused by vibration-induced motions. The principal low-level dynamic sources of these environments are spacecraft system deployments, articulation of solar arrays, attitude control maneuvers, as well as other mechanical system operations. These low-level vibrations may induce microphonics or jitter effects in many of the Europa Clipper science instruments or spacecraft system components.

The Europa Clipper microphonics and jitter environments at the victims' interfaces are currently being derived. The approach is to, first, identify and characterize all potential in-flight vibration environment for all sources from the subsystems and instruments, especially those in close proximity to sensitive instruments. Major known sources include the heat redistribution thermal pump, cryocoolers, reaction wheels, solar array drive, gimbal actuators, and mirror scanner. This is followed by an assessment of the sensitivity of the instruments or components to low-level vibrations, along with the definition of the adverse effects. Subsequently, a prediction of the response of the victims to the disturbance sources will be made with an analytical model. These modeling results will guide the development of a set of low-level vibration requirements to limit the vibration emissions from the sources. If the vibration levels are higher than the maximum emission limits, mitigations may need to be implemented, such as installing vibration isolators for the individual sources. Ultimately, a test of the sensitive instruments and components will be conducted to quantify their adverse effects and verify that they meet all the functional and science requirements.

THERMAL ENVIRONMENT

The Europa Clipper thermal environment is driven by the temperature extremes due to the Europa location/distance at the cold side and to the Venus gravity assist at the hot side. The solar flux at Europa at 5.6 AU is only 43.6 W/m². With a worst-case Jupiter eclipse of 9.2 hours, this makes the cold temperature the most extreme. The predicted worst-case cold temperature for components that are directly exposed to space without temperature control and non-operating is -240°C for the deployed REASON antenna elements. Meanwhile, the EVEEGA trajectory option brings Europa Clipper to near Venus at 0.65 AU with a solar flux of 3237 W/m² (compared with the mean solar flux near Earth of 1367.5 W/m²). The predicted worst-case hot temperature for components near Venus is 175°C for high gain antenna. Under certain operating conditions, the thermal louver blades, when in unstressed (partially open) condition, can reach as high as 380°C. For some components, the planetary protection bake-out (Dry Heat Microbial Reduction, DHMR) temperature of 125°C for long durations can be a driving requirement, particularly for electronic assemblies.

The Europa Clipper thermal architecture is an active control heat redistribution system with a single phase, mechanically pumped fluid loop routed across the flight system to control the temperatures of all the electronics and sensitive equipment to reasonable ranges. The predicted Allowable Flight Temperatures (AFTs) for all assemblies or components have been specified, together with the margined Flight Acceptance (FA), Protoflight (PF), and Qualification (Q) test temperatures for both operational and non-operational conditions. The margin for FA is AFT±5 °C and for Q/PF is AFT+20 °C/AFT-15 °C. These are all documented in a Temperature Requirements Table (TRT). The non-operational AFT test limits will be augmented to encompass the planetary protection bake-out temperatures, as necessary, for those assemblies that require DHMR bake-out.

For the Europa Clipper mission, all flight hardware is required to undergo a PF or a FA (after Q with an engineering unit) thermal vacuum test at the assembly, subsystem, or instrument level according to the temperature test limits specified in the TRT. This test is to demonstrate hardware performance within specifications throughout the temperature extremes, with margins, and to the specified durations. After all the assemblies, subsystems, and instruments have been

integrated into the flight system, it will undergo a thermal balance test to verify the flight hardware system thermal control design is able to maintain the AFTs, thermal gradients, and thermal stability requirements under a combination of extreme simulated mission thermal environmental and operational conditions.

OTHER ENVIRONMENTS

In addition to the driving environments, there are other less severe environments which still requires verification. These are described briefly in this section.

Meteoroid and Orbital Debris Environment

The Europa Clipper meteoroid environment includes meteoroid contributions from near Earth, during cruise, and in the vicinity of Jupiter/Europa orbit; and from space debris in the near-Earth vicinity. The mission fluence versus mass and speed distribution has been generated using the EVEGA trajectory, which gives an upper bound of the meteoroid environment for the longer mission duration. The Europa Clipper flight system requirement is to have a $\geq 95\%$ probability of surviving the Micrometeoroid and Orbital Debris (MMOD) environment to complete the minimum mission science return. The radiation vaults will provide good meteoroid protection. However, the exposed components and instruments will need to use best engineering practices or shielding to avoid meteoroid damage for the most vulnerable components, such as the propellant tanks, fluid loop pipes, or harnesses. The ultimate verification for this requirement is a flight system MMOD survival analysis that takes into account all the vulnerability contributions from each subsystem.

Atomic Oxygen Environment

The atomic oxygen environment is not expected to be a driving environment, but the flight system is still required to be designed to survive and operate within specifications under the atomic oxygen environment. The worst-case atomic oxygen fluence for the Europa Clipper mission has been defined. The contribution is primarily from near-Earth with insignificant contributions from the Jupiter torus and Europa atmosphere. The verification is simply a review of the

materials, that are exposed to space with a vector in the ram direction, to make sure they maintain acceptable property characteristics after exposure to the mission atomic oxygen fluence.

Solar Electromagnetic Environment

Solar electromagnetic environment (primarily the UV part of the solar spectral irradiance) is not expected to be a driving environment since the flight system spends a relative short time near-Earth. The solar spectral irradiance in the frequency range of 0.0850 - 7.0 Microns has been provided. **Paints and solar cell coverglass will be tested at mission expected levels.** The verification for most other materials will simply be a review to make sure the materials maintain acceptable property characteristics after exposure to UV irradiation.

ENVIRONMENTAL VERIFICATION SUMMARY AND CONCLUSIONS

A comprehensive description of the Europa Clipper mission and its challenging environments are provided. The mitigations activities to ensure compliance with the severe environments are presented. The environmental verification of all hardware at the assembly/subsystem/instrument level or at the flight system level is reported. This space verification campaign includes vibration/structural, acoustics, shock, thermal vacuum, radiation, EMC/EMI, and magnetics testing and/or analysis, as summarize in Table 1. The project is moving onto the detailed design phase and ready to implement this environmental verification program.

Table 1. Environmental Verification Summary

Assembly/Subsystem/Instrument	Flight System
Dynamics Environment <ul style="list-style-type: none"> • Random vibration test (including frequency survey) • Acoustics test (selected susceptible hardware) • Shock simulation test Thermal Environment <ul style="list-style-type: none"> • Thermal vacuum test • Thermal cycling life test/assessment (external items) EMI/EMC/Magnetics Environment <ul style="list-style-type: none"> • Conducted susceptibility/emission test • Radiated susceptibility/emission test • Grounding & isolation test 	Dynamics Environment <ul style="list-style-type: none"> • Quasi-static loads (pull) test • Random vibration test (including frequency survey) • Acoustics test • Pyrofiring test Thermal Environment <ul style="list-style-type: none"> • Thermal balance/vacuum test EMI/EMC/Magnetics Environment <ul style="list-style-type: none"> • Radiated emission test

<ul style="list-style-type: none"> • Magnetic emissions test/assessment • Magnetic moment test/analysis • Multipacting/ionization breakdown (corona) test <p>Radiation Environment</p> <ul style="list-style-type: none"> • Radiation (TID, DDD, SEE, iESD) tests/analyses <p>Other Environments</p> <ul style="list-style-type: none"> • Quasi-static loads analysis • Venting (depressurization) analysis • MMOD assessment • Atomic oxygen assessment • Solar spectral irradiance (UV) assessment 	<ul style="list-style-type: none"> • Radiated susceptibility test • Plugs out, self-compatibility test • Magnetic cleanliness test <p>Other Environments</p> <ul style="list-style-type: none"> • MMOD analysis (probability of survival & shielding)
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